Number Forms in the Brain

Joey Tang[1,2], Jamie Ward[1], and Brian Butterworth[1]

Abstract

■ Mental images of number lines, Galton's "number forms" (NF), are a useful way of investigating the relation between number and space. Here we report the first neuroimaging study of number-form synesthesia, investigating 10 synesthetes with NFs going from left to right compared with matched controls. Neuroimaging with functional magnetic resonance imaging revealed no difference in brain activation during a task focused on number magnitude but, in a comparable task on number order, synesthetes showed additional activations in the left and right posterior intraparietal sulci, suggesting that NFs are essentially ordinal in nature. Our results suggest that there are separate but partially overlapping neural circuits for the processing of ordinal and cardinal numbers, irrespective of the presence of an NF, but a core region in the anterior intraparietal sulcus representing (cardinal) number meaning appears to be activated autonomously, irrespective of task. This article provides an important extension beyond previous studies that have focused on word–color or grapheme–color synesthesia. ■

INTRODUCTION

"Number forms" (NFs), mental images of the sequence of numbers, are experienced by 12% of us, and were first reported scientifically by Galton (1880a, 1880b). These images are automatically activated and are often reported to play a role in numerical tasks including counting and calculation (Seron, Pesenti, Noel, Deloche, & Cornet, 1992). In one case, neurological damage led to both loss of the NF and to an inability to calculate (Spalding & Zangwill, 1950). Individuals with NFs may represent a consciously perceived example of a ubiquitous, but typically unconscious, number–space relationship (see Hubbard, Piazza, Pinel, & Dehaene, 2005). In Western cultures, at least, viewing or responding to numbers is associated with spatial biases such that lower numbers are more leftward (e.g., Fischer, Castel, Dodd, & Pratt, 2003; Dehaene, Bossini, & Giraux, 1993). One theory suggests that numbers are comprehended using an analog scale—a so-called mental number line—in which different numerical quantities can be understood in terms of the relative distances along this left-to-right oriented line (e.g., Pinel, Piazza, Le Bihan, & Dehaene, 2004), which can be affected by disorders of spatial cognition (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; Zorzi, Priftis, & Umilta, 2002).

The conscious merging of spatial and numerical representations is a form of synesthesia where an otherwise normal person experiences sensations in one modality when a second modality is stimulated. For example, a synesthete may experience a specific color whenever she encounters a particular tone (e.g., C-sharp may be blue) or may see any given number as always tinged a certain color (e.g., "5" may be green and "6" may be red; Ramachandran & Hubbard, 2001). In fact, synesthetes who perceive colors for numerals show five times the prevalence of NFs when compared with nonsynesthetic subjects (Sagiv, Simner, Collins, Butterworth, & Ward, 2006). Synesthesia is believed to utilize the same neural resources that support "normal" conscious perception (Sagiv & Ward, 2006). Thus, synesthetic experiences of color have been found to activate human area V4 (Sperling, Prvulovic, Linden, Singer, & Stirn, 2006; Steven, Hansen, & Blakemore, 2006; Hubbard, Arman, Ramachandran, & Boynton, 2005; Nunn et al., 2002; for a review, see Hubbard & Ramachandran, 2005) and, by hypothesis, we would expect NFs to activate neural regions that support conscious spatial perception such as those that reside in the parietal lobes. One suggestion for why NFs are so common in the general population, and why unconscious number–space interactions may be ubiquitous, is because of the proximity of neural circuits involved in number cognition and those involving spatial processing. The processing of numbers may automatically lead to cross-activation of adjacent neural regions involved in space perception, with this effect exaggerated in NF synesthetes (Hubbard, Piazza, et al., 2005; Ramachandran & Hubbard, 2001). However, the neural processing of numbers takes place in a number of stages and it is, at present, unclear which aspects of number are imbued with this spatial dimension.

Numbers are used to denote three different object properties: their quantity (i.e., cardinality, "three buses"), their position in a sequence (i.e., ordinality, "the third bus"), and language-based labels ("the number 3 bus"; for a review, see Nieder, 2005). Although cardinals and ordinals are normally in one-to-one correspondence, their

[1]University College London, [2]University of Hong Kong

representations dissociate in neurological patients (Delazer & Butterworth, 1997) and can be independently elicited in experiments with neurologically healthy participants (Turconi, Jemel, Rossion, & Seron, 2004). NFs are typically described as the sequence of digits, which is consistent with an ordinal representation, and individuals reporting NFs typically report mental images for non-quantitative ordinal sequences such as months and letters (Sagiv et al., 2006). The study of NFs could therefore illuminate the nature of the mental representation of number and the nature of number–space interactions in the brain.

The neural processing of numbers in the brain takes place in several distinct stages: The right fusiform gyrus is implicated in the identification of Arabic numerals (Pinel, Dehaene, Riviere, & Le Bihan, 2001; Pinel et al., 1999), and the cardinal meaning of the numeral in the bilateral *anterior* intraparietal sulcus [IPS] (Pinel et al., 2004; see also Fias, Lammertyn, Caessens, & Orban, 2007). Monkey cardinal processing also involves the IPS (Nieder, 2005). Processing of spatial information involves the *posterior* IPS homologous to the lateral and ventral IPS in monkeys (Ben Hamed, Duhamel, Bremmer, & Graf, 2001; Duhamel, Bremmer, Ben Hamed, & Graf, 1997). Mental numerical and spatial representations, as revealed in patients with difficulties in attending to one side of space (unilateral spatial neglect), implicate fronto-parietal regions (Zorzi et al., 2002). Based on the descriptions given by synesthetes that NFs are evoked in a variety of contexts (Seron et al., 1992), one might expect the NFs and their corresponding parietal region (posterior IPS, Hubbard, Piazza, et al., 2005) to be evoked in all types of number tasks, regardless of whether they are ordinal in nature or not. Here we make a more specific prediction that the patterns of the posterior IPS activation would differ between the synesthetes and the controls only in the ordinal tasks, but not in the cardinal task. In this study, NFs were investigated for the first time using functional magnetic resonance imaging (fMRI).

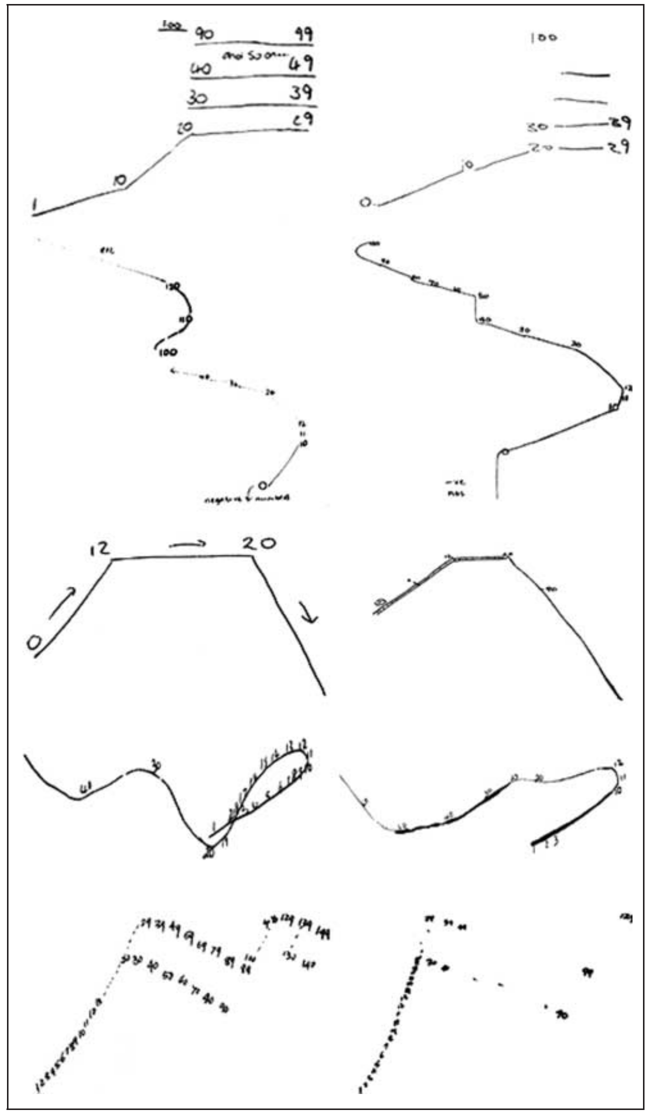

Figure 1. Examples of NFs drawn by some of our participants. The NFs were drawn on two separate occasions (first occasion on left, second occasion at 13 months later on average). All experienced the numbers 1–10 in a general left–right direction.

METHODS

Participants

Two groups of 10 participants were employed: individuals who reported having a NF and matched control participants. An NF drawing was obtained from each of the synesthetes during the study. These were consistent with original drawings submitted between 8 and 15 months previously. Examples of NFs drawn by some of our participants are shown in Figure 1.

The selection criteria for the synesthetes were that individuals do not have synesthetic experiences with colors, tastes, smells, noises, music, pain, and touch, and that their NF is of a general direction from left-to-right at least for small numbers (<10). They may have mental form representations for other sequences, for instance, days of the week, months of the year, temperatures, weight, height, and other quantities. The mean age of this group was 50.1 years (range = 22 to 76 years). There were eight women and two men. Eight of the synesthetes were right-handed; the rest were left-handed. The 10 control participants were matched to individual synesthetes by age, sex, and handedness. The mean age of this group was 51.0 years (range = 24 to 72 years). All participants were native English speakers. None of them had learnt any language that reads from right to left. Participants gave informed consent and the experiment was approved by the UCL ethics committee.

Behavioral Testing

Number Comparison Task

Previous research has found that NF synesthetes are slower when asked to judge which of two numbers is larger or smaller if the numbers are displayed in a format that is spatially incompatible with their NF relative to a spatially compatible condition (Piazza, Pinel, & Dehaene, 2006; Sagiv et al., 2006). Two number comparison tasks were performed in addition to the main study conducted in the scanner. In each trial, two numbers were presented on the screen for a maximum of 3000 msec and participants were required to press the button on the corresponding side of the larger or smaller number. Each of the two tasks had 56 trials. By collapsing together the two tasks (selecting the larger or smaller number), the spatial correspondence confound could be avoided. Two dummy trials were also added to the beginning of each task, but these were discarded for behavioral analyses. Practice trials were given prior to the start of the tasks.

Cardinal versus Ordinal Tasks

We devised two new experimental paradigms to dissociate cardinal and ordinal representations (see Table 1). In the cardinal task, participants had to decide whether a numeral corresponded with the number of items in a string (e.g., XX4X contains 4 items and the numeral ''4''). In the ordinal task, participants had to decide whether a numeral was in the correct position in the string. The task could be performed in a left-to-right direction (e.g., XX3X contains the numeral in the correct, third, position), or right-to-left direction (e.g., XX3X contains the numeral 3 in the incorrect, second, position). As such, the tasks are matched in terms of perceptual nature of the stimuli but differ only in terms of the cognitive demands of the task. Conflict trials are defined by a mismatch between the relevant dimensions, that is, when the correct response is ''no.'' The array size (numerosity) varied from three to five items, whereas the digit identity ranged from −2 to +2 of the numerosity. In other words, the digits ranged from 1 to 7.

Table 1. Sample Trials of the Cardinal and Ordinal Tasks

	Cardinal Task	*Ordinal Task (with Starting Point from the Left)*	*Ordinal Task (with Starting Point from the Right)*
X X X 5 X	Yes	No	No
X X X X 5	Yes	Yes	No
X 5 X X X	Yes	No	No
5 X X X X	Yes	No	Yes
X X X X 4	No	No	No
X X X 4 X	No	Yes	No
X 4 X X X	No	No	Yes

In the cardinal task, subjects were asked to judge whether the numeral corresponded to the number of items in the display. In ordinal tasks, subjects were asked to judge whether the numeral n was in nth position, starting from the left, in one condition, and nth from the right in a second condition. Nonconflict trials are where the numeral corresponds in cardinal task to the number of items, and to the nth item in the ordinal tasks and are labeled ''Yes''; the conflict trials are those where the numeral does not correspond to the number of items or to the nth position, and are labeled ''No.''

There was a total of three blocks: one cardinal task and two ordinal tasks. The cardinal task had 138 trials and each of the ordinal tasks had 144 trials (two dummy trials at the beginning were removed from the behavioral analyses). All participants performed the cardinal task and two ordinal tasks in the 3-T Allegra scanner (Siemens, Erlangen Germany) at the Wellcome Trust Centre for Neuroimaging at University College London. Practice trials were given prior to the scanning. Half of the participants performed the cardinal task first, followed by the two ordinal tasks, and the other half did the reverse. Ordinal tasks were never interrupted by a cardinal task. The order of the ordinal tasks was also counterbalanced. Half of the participants were assigned the left key for the ''yes'' response and right key for the ''no'' response, and the other half the reverse. Participants used their thumbs to make key responses.

Each trial began with a fixation cross of 500 msec. Then the stimulus array appeared for a maximum of 3000 msec, during which the participants were required to make a response. The stimulus array would disappear upon a keypress. At 3000 msec after the onset of the stimulus array, a blank screen of 500 msec would appear before the subsequent trial.

Scanning Procedures and Imaging Data Processing

The cardinal and ordinal tasks were performed during fMRI in order to elucidate the neural substrates of ordinal and cardinal number processing, and to examine the neural basis of NFs.

Whole-brain fMRI data were acquired with a gradient echo-planar sequence using blood oxygenation level-dependent contrast, each comprising a full brain volume of 40 contiguous axial slices of 2 mm thickness. Volumes were acquired continuously with a repetition time (TR) of 2.6 sec. A total of 220 scans were acquired for each participant in three sessions (approximately 10 min each), with the first 6 volumes subsequently discarded to allow for T1 equilibration effects. During fMRI scanning, pupil diameter was recorded on-line by an infrared eye tracker. The data were analyzed using SPM5 (Wellcome Department of Imaging Neuroscience; www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB 7.1.0.246 Release 14. Individual scans were realigned, slice time-corrected, normalized to the MNI template with voxels of $2 \times 2 \times 2$ mm^3, and spatially smoothed by an 8-mm full-width half-maximum Gaussian kernel using standard SPM methods.

Event-related activity for each voxel, for each condition, and for each subject was modeled using a canonical hemodynamic response function plus temporal and dispersion derivatives. Also included as confounds in the model were six movement parameters estimated in the realignment stage (de Lange, Hagoort, & Toni, 2005) and a pupillary repressor to account for the decrease in alertness (Kampe, Frith, & Frith, 2003). Statistical parametric maps of the t statistic (SPM{t}) were generated for each subject.

At the second-level random effects analysis, a $2 \times 3 \times 3$ analysis of variance (ANOVA) model was applied; the factors were group (synesthetes and controls), task (cardinal task, ordinal task from the left, and ordinal task from the right), and trial type (nonconflict, conflict, and error trials). t contrasts were constructed to compare groups, tasks, and trial types. Threshold significance was set at .001, uncorrected for main effects and interactions, and at .050, FDR correction was applied for further analyses.

RESULTS

Number Comparison Task

For the synesthetes, when the smaller number was presented on the left (i.e., spatially compatible to the individuals' NF), the mean reaction time (604 msec) was significantly faster than when the smaller number was presented on the right [619 msec; $t(9) = 2.47, p < .05$]. No such effect was found for the control group. This provides behavioral evidence for the authenticity of their NFs, similar to previous studies (Piazza et al., 2006; Sagiv et al., 2006).

The control participants' performance in the comparison task is consistent with Turconi, Campbell, and Seron's (2006) finding that a pair-order effect (faster reaction time when the smaller number was presented on the left than on the right) was observed during an order task (judging if the numbers are ascending or descending) but not during a quantity task (judging which number was larger).

Cardinal versus Ordinal Task

The response times were analyzed for correct trials only. The mean error rate for all tasks was <6%. Two $2 \times 2 \times 2$ ANOVAs were conducted: One compared the cardinal task with the two ordinal tasks collapsed together, whereas the other compared the two versions of the ordinal task. Apart from task, the other factors were trial (nonconflict and conflict) and group (controls and synesthetes). The first ANOVA comparing cardinal and ordinal tasks revealed a nonsignificant main effect of task [$F(1, 17) = 2.30$, *ns*], a significant main effect of trial [$F(1, 17) = 9.40, p < .050$], and a nonsignificant main effect of group [$F(1, 17) < 1$, *ns*]. There was no significant interaction (all *ns*). Mean reaction times were 828 and 880 msec for nonconflict and conflict trials, respectively. The second ANOVA comparing the two ordinal tasks revealed a significant main effect of task [$F(1, 17) = 4.90, p < .050$], a significant main effect of trial [$F(1, 17) = 5.72, p < .050$], and a nonsignificant main effect of group [$F(1, 17) < 1$, *ns*]. There was no significant interaction (all *ns*). Both groups responded significantly faster in the ordinal task with starting point on the left (L–R task) than that starting on the right (R–L task); mean reaction times were 801 and 854 msec, respectively. Both groups also responded significantly faster to nonconflict than conflict trials (mean reaction times were 807 and 849 msec, respectively).

Functional Imaging

The brain regions that are specific to the cardinal tasks can be identified by exclusively masking these with the activations observed in the ordinal tasks. No activation was observed in lateral parietal regions during the cardinal task in both groups of participants when analyzed together. The contrast (cardinal task–ordinal tasks) revealed enhanced activation in the bilateral precentral gyri, the left medial and inferior frontal gyri, the bilateral cingulate gyri, and the left precuneus. The reversed contrast showed activation in the left fusiform gyrus, several occipital regions (including the left superior occipital gyrus and the left cuneus), and the right inferior frontal gyrus. In this last contrast, the synesthetes showed a larger difference in activation than the control group in the bilateral precentral gyrus, the left inferior frontal gyrus, the right middle frontal gyrus, and several temporal regions (including left superior, middle, and inferior temporal gyri).

In order to identify brain regions common to both the cardinal and ordinal tasks, conjunction by inclusive masking was performed. The results from synesthetes and controls are summarized in Tables 2 and 3, respectively. When conjunction by inclusive masking was performed across the three tasks, bilateral activation in and around the anterior IPS was observed in both groups. This region has typically been considered the core of the semantic representation for numbers (e.g., the following region was identified in a recent meta-analysis: $x = -44, y = -48, z = 47$ and $x = 41, y = -47, z = 48$; Dehaene, Piazza, Pinel, & Cohen, 2003). The fact that it is activated in all tasks suggests that its activation is autonomous (e.g., Tang, Critchley, Glaser, Dolan, & Butterworth, 2006), even when the ordinal properties of numbers are attended to. As such, the present study provides the first evidence from functional imaging to show that cardinal and ordinal processing of numbers activates different but partially overlapping neural circuits. This is consistent with previous electrophysiological (Turconi et al., 2004) and neuropsychological (e.g., Delazer & Butterworth, 1997) studies.

The critical contrast in the neuroimaging investigation was the Task by Group interaction. With regard to the two ordinal tasks, the following regions showed

Table 2. Regions Activated across All Three Tasks (Cardinal and Ordinal) for the Synesthetes

		Talairach Coordinates			
No. of Voxels	*Z*	*x*	*y*	*z*	
800	5.36*	4	8	49	Right superior frontal gyrus
	4.72*	6	16	42	Right cingulate gyrus
	4.64*	−8	18	43	Left medial frontal gyrus
180	4.42*	−53	−29	47	Left anterior intraparietal sulcus
	3.34	−40	−42	52	Left anterior intraparietal sulcus
137	4.04*	32	1	53	Right middle frontal gyrus
20	3.95*	−26	−11	54	Left precentral gyrus
21	3.87*	−18	−58	53	Left precuneus
23	3.74*	53	−25	47	Right postcentral gyrus
36	3.43	44	−33	46	Right anterior intraparietal sulcus (bank)

Conjunction by inclusive masking.

$p < .001$ (uncorrected).

*$p \leq .050$ (with FDR correction).

Table 3. Regions Activated across All Three Tasks (Cardinal and Ordinal) for the Controls

		Talairach Coordinates			
No. of Voxels	*Z*	*x*	*y*	*z*	
617	4.93*	−2	18	40	Right cingulate gyrus
	4.59*	0	10	53	Interhemispheric
133	4.44*	−48	8	36	Left middle frontal gyrus
	3.45*	−44	7	24	Left inferior frontal gyrus
365	4.31*	−32	−48	48	Left anterior intraparietal sulcus
	4.05*	−48	−35	39	Left anterior intraparietal sulcus
	3.96*	−36	−43	39	Left anterior intraparietal sulcus
69	4.04*	40	42	20	Right middle frontal gyrus
45	3.84*	53	7	31	Right inferior frontal gyrus
95	3.74*	46	−39	44	Right anterior intraparietal sulcus
	3.37*	51	−31	48	Right postcentral gyrus
14	3.68*	−28	−58	53	Left superior parietal lobule
13	3.42*	−36	16	1	Left insula
28	3.40*	−44	40	15	Left middle frontal gyrus
9	3.32*	57	21	1	Right inferior frontal gyrus
12	3.32*	36	−42	52	Right anterior intraparietal sulcus (bank)
6	3.30*	−22	−1	48	Left frontal subgyral

Conjunction by inclusive masking.

$p < .001$ (uncorrected).

*$p \leq .050$ (with FDR correction).

significantly stronger activation in the synesthetes than in controls during the L–R task compared to the R–L task: bilateral precentral gyri, left superior frontal gyrus, right middle frontal gyrus, left superior temporal gyrus, right middle temporal gyrus, bilateral cingulate gyri, left insula, and several parietal regions including the left superior partial lobule, and along the banks of the posterior IPS (left: $x = -24, y = -58, z = 54$; right: $x = 38, y = -50, z = 52$).

Further analyses were separately carried out for the two groups. When the synesthetes performed the L–R ordinal task, activation was observed in several regions including the bilateral posterior IPS (left: $x = -32$, $y = -58$, $z = 51$ and $x = -26$, $y = -68$, $z = 33$; right: $x = 42$, $y = -54$, $z = 40$), the left insula, and several frontal regions predominantly on the right (see Figure 2). These regions were not activated in the R–L ordinal task or the cardinal task (contrast by exclusively masking; see Table 4). When the same contrast was tested with the control group, no significant activation was found. Moreover, no significant activations were found in the synesthetes relative to the controls when the R–L ordinal task was contrasted with the other tasks. This suggests that although differences exist between NF synesthetes and controls, these differences are modulated by the task and are most apparent when the demands of the task are spatially similar to their NF representation.

No significant voxel emerged in the contrast (conflict trials–nonconflict trials) and there was no significant Conflict × Group interaction. On the other hand, the contrast (error trials–correct trials) revealed enhanced activation in the bilateral anterior cingulate, the bilateral middle and inferior frontal gyri, the right precentral gyrus, the bilateral supramarginal gyri, the left inferior parietal lobule, and several temporal regions (including the bilateral middle temporal gyri, the left superior temporal gyrus, and the right transverse temporal gyrus). The synesthetes showed a larger difference in activation than the control group in the right inferior frontal gyrus and in the left precentral gyrus. Enhanced activation in the right inferior frontal gyrus has been associated with informational conflict in a numerical comparison Stroop task (Tang et al., 2006) and activation in the anterior cingulate cortex has previously been associated with error commission (e.g., Carter et al., 1998).

DISCUSSION

The findings of the present study support the conclusion that the cardinal and ordinal representation of numbers recruits partially separable neural circuits (Turconi et al., 2004; Turconi & Seron, 2002; Delazer & Butterworth, 1997). One region in the anterior IPS has previously been associated with cardinal number meaning, and this activation appears to occur automatically even when the participant attends to the ordinal position of a number in a sequence. A further aim of this study was to determine whether NFs—the conscious mental number

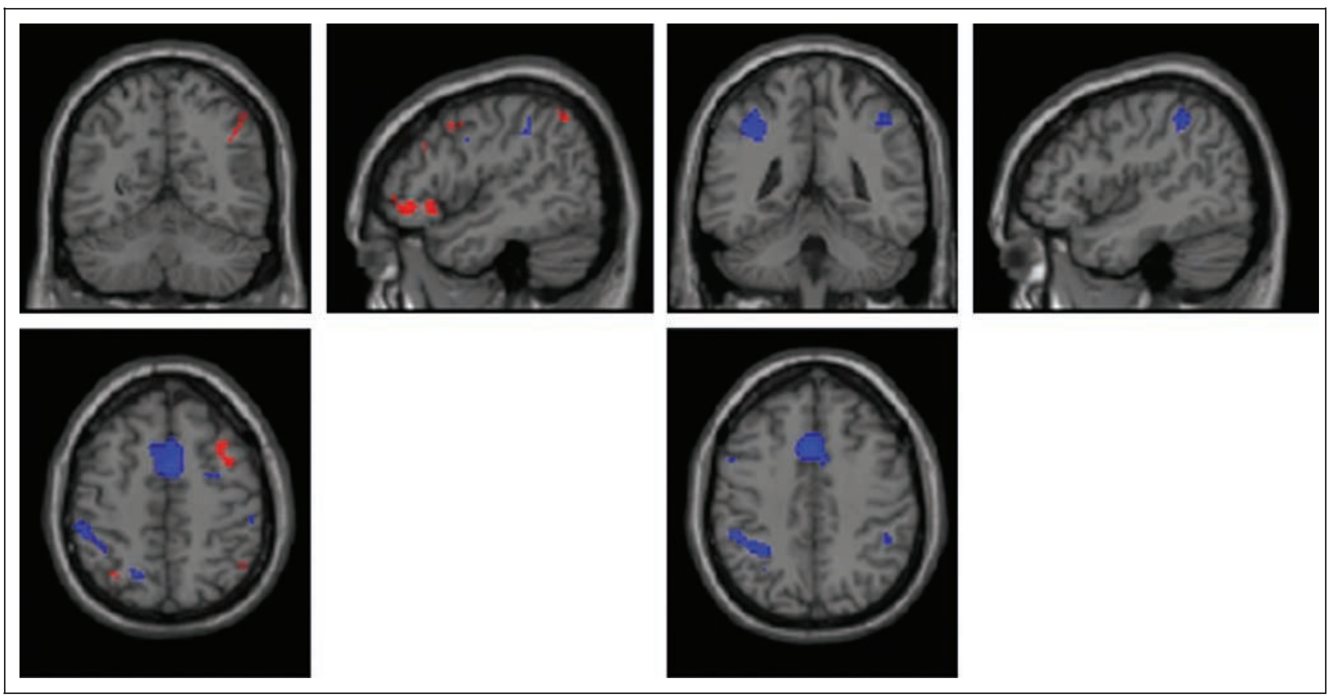

Figure 2. The figure on the left shows activated regions in participants with NFs (coronal section is at $x = 48$), and the figure on the right shows control participants (coronal section is at $x = 46$). Regions activated by both cardinal and ordinal tasks are shown in blue (conjunction by inclusive masking; see Tables 2 and 3). Regions activated by the left-to-right ordinal task are shown in red (exclusively masking other tasks; see Table 4). Both groups activated the anterior IPS bilaterally in all three tasks (blue), whereas only the synesthetes activated the bilateral posterior IPS in the ordinal task with starting point from the left (red).

Table 4. Regions Activated in the Synesthetes during the Ordinal Task with Starting Point from the Left

		Talairach Coordinates			
No. of Voxels	*Z*	*x*	*y*	*z*	
160	4.91*	46	38	−7	Right middle frontal gyrus
	4.16*	46	23	−5	Right inferior frontal gyrus
58	4.49*	4	25	37	Right cingulate gyrus
13	4.32*	42	35	30	Right superior frontal gyrus
20	4.32*	50	31	28	Right middle frontal gyrus
217	4.18*	42	10	44	Right middle frontal gyrus
	4.11*	30	4	40	Right frontal subgyral
	3.67*	32	−4	44	Right middle frontal gyrus
23	3.66*	59	−6	33	Right precentral gyrus
25	3.61*	−42	45	0	Left inferior frontal gyrus
42	3.58*	42	−54	40	Right posterior intraparietal sulcus
	3.45*	44	−60	49	Right superior parietal lobule
14	3.53*	−44	−26	20	Left insula
6	3.51*	−50	−41	43	Left inferior parietal lobule
6	3.41*	−32	−58	51	Left posterior intraparietal sulcus
8	3.37*	−26	−68	33	Left posterior intraparietal sulcus
7	3.29*	38	58	−6	Right middle frontal gyrus
6	3.29*	−6	−14	25	Left pons

Exclusively masking other tasks.

$p < .001$ (uncorrected).

$^*p \leq .050$ (with FDR correction).

line—are ordinal or cardinal in nature. Regions in the posterior IPS have been implicated in spatial processes relevant to number (Hubbard, Piazza, et al., 2005) and, indeed, we find bilateral activity in this region in NF synesthetes, but only when they make ordinal judgments in a left-to-right (L–R) direction, that is, when the synesthetes were, in effect, looking for stimuli that were presented in such a way that was spatially congruent to their NF. Our finding is consistent with the posterior IPS activation observed during congruent trials in auditory–visual (AV) matching tasks (Meienbrock, Naumer, Doehrmann, Singer, & Muckli, 2007; Saito et al., 2005).

Our findings present the first evidence from functional imaging to show that cardinal and ordinal processing of numbers activates different but partially overlapping neural circuits. Recently, Fias et al. (2007) have shown that the anterior IPS is activated in both number and letter comparison tasks, suggesting that this region is involved in the processing and representation of both numerical and nonnumerical ordinal sequences. However, their number comparison task involves selecting the larger of two numbers which may be solved using either ordinal representations (i.e., which number comes later in the sequence) or cardinal representations (i.e., which number is larger). The activation observed in IPS therefore does not differentiate between ordinal and cardinal processing of numbers. The tasks used in the present study, however, clearly differentiate between the two processes, and we have shown that different regions along the IPS are responsible for each of these processes—the anterior IPS for cardinal processing and the posterior IPS for ordinal processing.

Compared to mapping studies which have identified posterior parietal regions involved in saccadic eye movements ($x = 32$, $y = -68$, $z = 46$ in Sereno, Pitzalis, & Martinez, 2001) and spatial attention ($x = \pm 23$, $y = -76$, $z = 39$ and $x = \pm 19$, $y = -75$, $z = 48$ in Silver, Ress, & Heeger, 2005), the regions along the posterior IPS activated in the present study are not as posterior (left: $x = -32$, $y = -58$, $z = 51$ and $x = -26$, $y = -68$, $z = 33$; right: $x = 42$, $y = -54$, $z = 40$). This difference suggests that the spatial representations evoked by numbers in the posterior parietal lobes may be distinct from other spatial or visuospatial representations.

The more posterior region of the IPS is believed to be the human equivalent of regions identified in the monkey that code for eye-centered spatial frames of reference (lateral intraparietal region; Ben Hamed et al., 2001) and head-centered frames of reference (ventral intraparietal region; Duhamel et al., 1997). That is, it codes for locations of stimuli (in this instance the sequence of numbers) that are dependent on the position of the eyes or head, respectively. The regions that we identified are comparable to the ''posterior superior parietal lobe'' regions ($x = -22$, $y = -68$, $z = 56$ and $x = 15$, $y = -63$, $z = 56$) identified by a meta-analysis of several numerical tasks believed to have a spatial component (Dehaene et al., 2003). The activation of right prefrontal regions when the synesthetes made L–R ordinal judgments was not specifically predicted, but it is consistent with neuropsychological evidence that right prefrontal spatial working memory structures build up and keep the mental number line active (Doricchi et al., 2005). This may be particularly important for maintenance of a number sequence that is consciously perceived given the more general role of parieto-frontal circuits in conscious aspects of cognition (Rees & Lavie, 2001) and space perception in particular (Fogassi & Gallese, 2004). The region is also activated in other tasks involving number comparison (Tang et al., 2006).

The posterior IPS regions that we identified have been activated in a number of other studies of synesthesia. A caudal IPS region ($x = -24$, $y = -65$, $z = 51$) is activated by visually presented graphemes that evoke color (Weiss, Zilles, & Fink, 2005), and a region ($x = -30$, $y = -62$, $z = 40$) associated with grapheme–color synesthesia is elicited by speech (Paulesu et al., 1995), in both cases, spatial forms may have been activated, given the fact that grapheme–color synesthesia and spatial forms often co-occur (Sagiv et al., 2006). An alternative explanation is that these regions have a more general function in synesthesia, for example, in the spatial binding of different stimulus attributes irrespective of whether forms are involved (Ward, Li, Salih, & Sagiv, 2007; Robertson, 2003).

Our results support the hypothesis that NFs—the conscious mental number line—is ordinal in nature and represents the sequence of numerals as they have been learned by these numerate subjects. This is not to say that NFs are a purely learned phenomenon. The tendency to associate numbers and space is probably not learned, although the particular sequence of numbers found in a given language is learned, as is the direction of reading. Previous research on spatial response biases in processing numbers suggests that the left-to-right bias is diminished in Persian speakers (Dehaene et al., 1993), although it remains to be seen whether the majority of NFs show a direction reversal in cultures that read right-to-left. Because the NF appears to be an ordinal construction out of the sequence of numerals, this is consistent with other spatial effects over nonnumerical ordinal sequences such as letters and months of the year (Sagiv et al., 2006; Gevers, Reynvoet, & Fias, 2003).

The fact that nonsynesthetes did not show activation in the posterior IPS in the L–R ordinal task suggests that the conscious NF is neurally distinct from the unconscious number–space interactions revealed by indirect measures (Fischer et al., 2003; Dehaene et al., 1993). This distinction has been suggested to explain the dissociation between mental number bisection and Spatial Numerical Association of Response Codes (SNARC) performance in left hemispatial neglect patients (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006). During the mental number bisection task, the neglect patients explicitly accessed their visuospatial representation of numbers and ignored the left hemispace. However, these patients did not show left hemispatial neglect during a modified version of the implicit SNARC task (Priftis et al., 2006). A more striking example is a single case of synesthesia showing a dissociation between explicit and implicit spatial–numerical associations; the synesthete has an explicit R–L NF but showed a normal left-to-right pattern on an indirect measure (Piazza et al., 2006). In terms of our present findings, only the synesthetes have an NF to which they explicitly accessed during the L–R task, providing them a facilitation effect associated with posterior IPS activation. Control participants, on the other hand, do not possess a conscious NF, hence a lack of activation in this region.

Our findings suggest that spatial–numerical representations are task-specific. Different spatial reference frames (e.g., explicit vs. implicit) may support different aspects of numerical cognition. The existence of NFs could be seen as one particular variant of a wider range of number–space interactions that have their origins in the IPS.

Acknowledgments

This research was supported by a grant from the Leverhulme Trust to J. W. and B. B. We thank Professor Chris Frith of the Functional Imaging Laboratory (UCL) for supporting this research, and Professor Tetsuro Matsuzawa of the Primate Research Institute (Kyoto University) for suggesting the idea of an ordinal Stroop task. J. T. designed the experiments, tested participants, and analyzed data. B. B. and J. W. contributed to design and interpretation, and J. W. maintains a database of synesthetes from which participants were drawn.

Reprint requests should be sent to Joey Tang, Department of Psychology, The University of Hong Kong, Pok Fu Lam Road, Hong Kong, or via e-mail: joeytang@hku.hk.

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